DETERMINATION OF THE TIDE IN THE OFFING FROM TIDAL STREAM DATA.

Application to Tides of the Central Channel between the meridian of Cherbourg and the meridian of Fécamp.

(The following is an extract from an article by Mr. Henri LACOMBE, *Ing. hydrographe principal*, published in the *Annales Hydrographiques*. Paris, 1949).

FOREWORD.

Reduction of soundings made in Hydrographic Surveys to theoretical datum necessitates an accurate knowledge of the tide throughout the area surveyed, in the vicinity of the coast as well as in the offing. Now, owing to the present lack of any apparatus suitable for recording tide in the offing at relatively great depths (16 to 54 fathoms), the tide is usually observed along the shore only, and the soundings taken in the offing are reduced on the basis of such observed tide. Where the tide is subject to important variations along the shore, reduction is operated according to " tidal zones " in each of which the tide, to a certain selected degree of approximation, is considered as connected by a more or less correct empiric law to that already determined for a selected part of the coast. The delimitation of such areas, relatively easy near the shore, is somewhat arbitrary in the offing where, through lack of observations, the progression direction of the tide is but little known. As a result, reduction of the soundings is generally not very accurate; this fact, however, hardly comes within the knowledge of the mariner for in order to determine the sounding to be plotted on the chart according to the indications of his sounding apparatus, he also makes use of the tide on the shore or, rather, of the tide at the nearest port for which the Tide Tables show the predictions.

The present article suggests a method largely permitting elimination of the arbitrary distribution of the " tidal zones " and the determination, at least approximately, of the tide wherever tidal stream measurements can suitably be made.

If *tide* properly so-called is rarely observed in the offing, there is nevertheless one aspect of the phenomenon which is the subject of systematic measurements carried out relatively far from land, consisting namely of *tidal streams*, which are measured by means of an extensively used and reliable apparatus, several satisfactory types of which are in existence. It is moreover clear that level displacement and tidal streams must be connected, since both are different aspects of the same phenomenon.

The equations of hydrodynamics make it possible, starting from tidal observation along the shore (limit conditions) and from tidal stream observation at several stations in the offing, to deduce the tide in the offing from the tide along the shore and to establish " concordance " between the two; from this results a satisfactory distribution of the various tidal areas and a better knowledge of tide in the offing, from the theoretical point of view.

Even should reliable recording tide gauges for tide in the offing one day be available, measurement of streams will maintain its value *from the point of view of navigation* for, if the mariner is greatly interested in the tide, especially at harbour entrances, he pays more attention in the offing to tidal streams, which save him long hours of navigation. Moreover, from the theoretical point of view, the tidal streams (as will be seen later) permit determination of the *plane tangent* to the surface of the sea at any time for points where tidal stream measurements are available; and this constitutes a very useful supplement to knowledge of elevation level which might be given by any future tide recorder. Finally, if it is possible to deduce from tidal stream data, often with sufficient approximation, the tide which at a given moment involves one single unknown quantity (value of elevation level), it must be realised that unless simplifying assumptions be introduced, the reverse process is more difficult, since at all times the stream involves two parameters (velocity and direction). The practical and theoretical necessity of tidal stream measurement therefore remains.

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Mr. Lacombe then passes in review the principles of computation methods. These have been discussed by Proudman and Doodson (1924) and Doodson and Corkan (1932), having previously been dealt with by Defant (1923).

In view of the study the results of which are developed below, Mr. Lacombe retains the two following groups of expressions :-

1°

(5)
$$\left\{\begin{array}{l} \frac{\delta u}{\delta t} - 2\omega v \sin\varphi = - g \frac{\delta\zeta}{\delta x}. \\ \frac{\delta v}{\delta t} + 2\omega u \sin\varphi = - g \frac{\delta\zeta}{\delta y}. \end{array}\right.$$

where x and y are the co-ordinates of a particle of water referred to a horizontal plane of axes Ox, Oy, contrasolem, at time t; u and v the components along Ox and Oy of the velocity of the particle, ω the angular speed of earth rotation, φ the latitude, g the gravity, ζ elevation of the free surface referred to the equilibrium level; assuming that the viscosity coefficient and the rectangular terms of acceleration are negligible (i. e. perfect fluid and regularly-spaced lines of flow); assuming also that vertical velocity and acceleration are negligible (long waves),

2°

(8)
$$\left\{\begin{array}{l} g \frac{\delta\zeta}{\delta R} = 2\omega V \sin\varphi + \frac{V^2}{R}. \\ \frac{g}{R}\frac{\delta\zeta}{\delta\theta} = -\frac{V}{R}\frac{\delta V}{\delta\theta} - \frac{\delta V}{\delta t}. \end{array}\right.$$

which is the equation of the motion, where the rectangular terms of acceleration are considered in polar co-ordinates r and θ, referred to the motionless curvature centre of the lines of flow, R being the vector radius equal to the radius of curvature of the line of flow.

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I.—METHODS OF COMPUTATION.

Practical Use of Formulae (5) **and** (8).—Let *one hour* be the time unit; the *knot* the velocity unit; *the centimetre* the change of level unit; the *nautical mile* the distance unit : then equations (5) and (8) resolved in terms of surface gradient, are written :-

(5 a)
$$\frac{\delta\zeta}{\delta x} = -2{,}71 \frac{\delta u}{\delta t} + 1{,}42\, v \sin\varphi,$$

and

(8 a)
$$\frac{\delta\zeta}{\delta r} = 1{,}42\ V \sin\varphi + 2{,}71 \frac{V^2}{R}.$$

In equation (5 a) $\frac{du}{dt}$ may be substituted if required for $\frac{\delta u}{\delta t}$ and in equation (8 a) V should be taken as positive if the particle moves towards increasing values of θ and conversely.

Near latitude 49° 30', sin φ = 0.76, and (5 *a*) becomes (5 *b*) :-

$$\frac{\delta\zeta}{\delta x} = -\,2{,}71\,\frac{\delta u}{\delta t} + 1{,}07\,v. \qquad (5\,b)$$

Let the tidal stream stations A, B, C,... be connected, two by two. At point A, let us take AB for the x axis.

Tidal stream measurement provides, for each tidal hour reckoned from six hours before to six hours after predicted H. W. for a standard port, the components u and v of the tidal stream along Ox and along Oy, the "contrasolem" perpendicular. By plotting the curve u in terms of time, the angular coefficient of the tangent to the curve is deduced, giving in magnitude and in sign $\frac{\delta u}{\delta t}$.

Then formula (5 *b*) gives $\frac{\delta\zeta}{\delta x}$ at point A in the direction of Ox.

The same operation at B along the same direction AB, supplies the value $\frac{\delta\zeta}{\delta x}$ for the same direction Ox but at point B.

Passing now to section BC, let BC be the new x axis, whence the gradient $\frac{\delta\zeta}{\delta x}$ at B in the direction BC which differs from the preceding gradient if AB and BC are not in a single straight line.

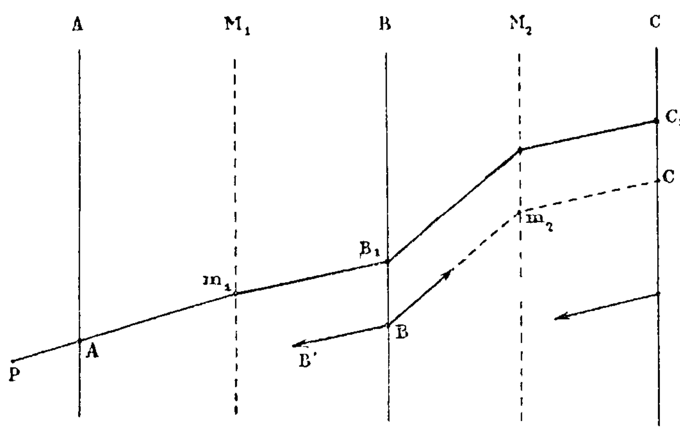


Fig. 1.

From the above, the successive gradients of sea surface at A (section AB), at B (section AB and BC), etc., are deduced. At B we have two gradients, one along AB and one along BC. Then the straight lines having gradients equal to gradients found are plotted (fig. 1) at the selected scale and from the latter the surface of the sea with reference to the level at point A are reconstituted. Assuming that the surface between A and B is an arc of a circle, the gradient at M. middle point of AB, should be the average of gradients at A and B (towards A); consequently, by taking the intersection m_I of segment AA', the gradient of which is known, with the straight line M and plotting through m_I the parallel to BB' characteristic of gradient at B (towards A), point B_I is obtained, and the circle through A and B_I closely approximates the surface of the sea between A and B, on condition that the latter points be not too distant, i. e., if the gradients at A and B (towards A) *are similar.* In the practical application which has been made, similar gradients have always been found at the extremities of sections such as AB. In this way the shape of the sea surface AB_IC_I is obtained by degrees. If point A is in the vicinity of the shore near a harbour P where the tide is known, elevation of water level at each point B, C, etc., is deduced for the tide under consideration in terms of the tide at point A.

Repeating this operation for each tidal hour, the tidal curve at the different tidal stream stations can be deduced along with elevation of water-level referred to the level surface passing through datum at harbour P in the vicinity of point A. If the elevation of mean level near point A is known, it will be possible at least theoretically to compare with it the mean level for intermediate points. At the extremity of a chain reaching the shore at a point where the tide is known, the "closure" is obtained by superposition of the mean levels, if there is no accurate levelling between the extreme points of the profile; this offers the possibility of adjustment of the whole of the elevation values.

Discussion of Accuracy and Consequent Deduction.—All the orientations of profiles ABC... are not equally favourable; indeed the accuracy of the term $\frac{\delta u}{\delta t}$ is less than that obtained for the component v since the maximum possible error of $\frac{\delta u}{\delta t}$ which is finally obtained by means of a difference, is normally double that of the maximum possible error of u and of v.

On the other hand, the coefficient of the term $\frac{\delta u}{\delta t}$ is about 2.5 times larger than the coefficient of the term v. The result is that an error five times larger than the other is to be expected on the first term. It is therefore of capital interest to reduce as far as possible the term u, i.e., to *orient the profile according to the perpendiculars of the lines* of flow. In case the latter have a practically fixed direction, as is usual near the shore and particularly in the Channel area (except for some small portions), the lines of flow have nearly fixed direction and the profiles have not to be modified according to the various tidal hours, which in practice would involve important complications.

We have seen above that this perpendicular condition of the profiles and lines of flow was the same as that which made the influence of friction negligible on sea-bottom and made the normal gradient of the surface, in areas where the curvature of the lines of flow is noticeable, independent of variations in space of the velocity; it alone suffices in fulfilling all the conditions for maximum accuracy.

Evaluation of the gradient errors to be expected :-

(a) *Profile perpendicular to lines of flow.*—(In the Channel) we have approximately :-

$$\frac{\delta \zeta}{\delta x} = 1{,}07\, v. \tag{11}$$

An error of 0.3 knots with respect to v— which is the order of magnitude of the mean error in the measurement—gives for the gradient an error of only 3 mm. per mile or 3 decimetres for 100 miles; the latter value is of the order of sounding accuracy in shallow waters.

(b) *Profile in the direction of the lines of flow.*—The profile being selected for the x axis, we have :-

$$\frac{\delta \zeta}{\delta x} = -\, 2{,}71\, \frac{\delta u}{\delta t}. \tag{12}$$

An error of 0.3 knot with respect to u may involve an error of 0.60 knot per hour in $\frac{\delta u}{\delta t}$, corresponding to a gradient error of 1.5 cm. per mile and 1.5 metres in 100 miles, which is considerable.

Similar calculations at neaps would involve similar absolute errors with respect to elevation : therefore double relative errors for amplitudes. Consequently, profiles orientated along the lines of flow must be avoided insofar as possible ; they have been reduced to a minimum in the following development and the application of the method in an attempt to connect, in the direction of the lines of flow, the bay of the Seine (Saint-Vaast) to Cherbourg following the coast, has produced important " closure " errors, especially when following a profile connecting the coastal stations sometimes situated in very shallow water in the vicinity of the Pointe de Barfleur. A " closure " more to the North gives smaller range discrepancies, not exceeding approximately 75 cm., between Le Havre and Cherbourg. However, the departures between the curve obtained and the typical curve of the latter port at a given hour may reach 1.25 metre, the coincidence of High Water being assured.

The restriction imposed by the direction to be given to the profile does not seem likely to be, in practice, very inconvenient for, along the coast, the currents are necessarily more or less parallel to it and the tide in the offing may be deduced from measurements made on profiles perpendicular to the coast and to the stream.

A few Deductions from Equation (11) :-

(a) *Rotation of the sea-surface level contours.*—From consideration of equation (11) and its analogue in $\frac{\delta\zeta}{\delta y}$

$$\frac{\delta\zeta}{\delta y} = -\,2{,}71\,\frac{\delta v}{\delta t}, \tag{13}$$

the Ox axis being perpendicular to the lines of flow ($u \equiv o$), we can deduce several interesting properties concerning relations between the gradients and the surface level curves and the currents.

In order to simplify the text let us assume that the flood current is East, the ebb current West (alternating current), the Ox axis directed towards the North, consequently the Oy axis towards the West. From equations (11) and (13) it results that, especially when the streams alternate (Channel), $\frac{\delta\zeta}{\delta y}$ cancels out when the stream reaches algebraically its maximum (ebb) and its minimum (flow). Consequently, when the rate of flow is maximum (at times, in the offing, approximating H. W. and L. W.) the direction of maximum steepness of the sea surface coincides with the perpendicular to the lines of flow.

Similarly, as the tidal stream very nearly has a sinusoidal characteristic, since it equals zero when its derivative with respect to time is maximum or minimum, it may be seen that for slack water periods, the greatest sea-surface gradient coincides with the lines of flow.

For intermediary times :-

When $\frac{\delta v}{\delta t}$ is positive, i. e., the Oy axis having been selected, between maximum flood and maximum ebb, $\frac{\delta\zeta}{\delta y}$ is negative and :

(a) If v is negative (decreasing flood), $\frac{\delta\zeta}{\delta x}$ is negative, the greatest gradient *downwards* is orientated between the North and the West;

(b) If v is positive (increasing ebb) $\frac{\delta\zeta}{\delta x}$ is positive, the greatest gradient downwards is orientated between West and South.

When $\frac{\delta v}{\delta t}$ is negative, i. e. between maximum ebb and maximum flood, $\frac{\delta\zeta}{\delta y}$ is positive and :

(a) If v is positive (decreasing ebb) $\frac{\delta\zeta}{\delta x}$ is positive and the greatest gradient downwards is orientated between South and East ;

(b) If v is negative (increasing flood) $\frac{\delta\zeta}{\delta x}$ is negative and the greatest gradient downwards is orientated between East and North.

Therefore, in a zone of the Northern hemisphere where the alternating current is roughly sinusoidal, the direction of the greatest gradient of the surface rotates according to time anticlockwise (*contrasolem*); in the Southern hemisphere the direction of rotation is reversed (also *contrasolem*).

From the preceding it may be deduced that the sea-surface *level contours* rotate *contrasolem* and make one revolution per tidal period.

If, in a system of currents approximately alternating and for a single component of the tide (M_2) there may exist an amphidromic point (virtually such in the case of the Channel), the above considerations permit us to find the direction of rotation of the cotidal lines at that point. As a matter of fact the zero contour (referred to mean sea level) constantly passes through the amphidromic point and the group of such level contour lines at that point rotates *contrasolem* making one revolution per period. But the zero level contour is at each moment a cotidal line; consequently these cotidal lines rotate about any possible amphidromic point, anticlockwise in the Northern hemisphere, during the tidal period.

(b) *Sensitivity of the Tidal Stream with reference to level variations in space.*—Equation (11) calls for an interesting observation : it shows that streams of the order of one knot co-exist, in our latitudes, together with surface gradients, according to the perpendiculars to the stream lines, of the order of 1 cm. per mile; gradients of this order are disclosed only by accurate levelling ashore. An observer at sea is absolutely unable to detect such gradients; he can easily detect the existence of a current of 1 knot however, in relatively shallow water. Consequently *the current is a very sensitive criterion for level variation* in a direction perpendicular to the current and conversely, *measurement of the velocity of the tidal current, even though approximate, will provide a satisfactory value for the sea-surface gradient* reckoned perpendicularly to the stream. Therefore, when discussing the natural phenomenon constituted by the tide, the factor " current " should be more accessible to measurement than the factor of " level variation " ; and as a consequence tidal current measuring apparatus may be more rudimentary than tide-recording gauges.

From the above it likewise follows that for profiles perpendicular to the lines of flow, slight current changes along the vertical due to friction on the sea-bottom should not give rise to important errors with respect to heights of the water.

(c) *Relationships with Permanent Ocean Currents.*—Calculation of permanent density currents in relation to mass distribution in the sea (Bjerknes Theory), leads to expressions similar to equation (5) which then takes the following form :-

$$2\omega v \sin\varphi = g\frac{\delta\zeta}{\delta x}$$

or

$$\frac{\delta\zeta}{\delta x} = 1{,}42\ v \sin\varphi$$

using the above selected units[1].

The selection of orientation of the profile perpendicularly to the instantaneous lines of flow of the stream has in a sort of way the effect of eliminating in the said direction the influence of the non-permanent character of the tidal stream. The gradient, *perpendicular to the lines of flow of the tidal stream*, coexistent with a given tidal current, consequently has the same value as the *maximum gradient* of the sea-surface coexistent with a permanent ocean density current, of the same value, in the absence of any other kind of current. However, for the tidal stream, the gradient perpendicular to the lines of flow is not the direction of maximum steepness except in particular cases (times of maximum flood and ebb).

II.—APPLICATION TO MID-CHANNEL.

Computation data.—(a) *Currents.* Between the meridian of Fécamp and the meridian of Cherbourg, numerous current observations have been made in the

(1) In such a case, however, the isobaric surfaces have a gradient dependent on z.

vicinity of Le Havre by the " Service Maritime " of that port (1929-1931), in the southern part of the sea by surveying parties of the " Service Hydrographique " (1908-1910 and 1935-1939) and in the northern part by the British Navy. When use was being made of all French measurements adjusted and upon communication by the Hydrographic Department of the British measurements, it appeared of interest to try to throw light upon the tidal system in that area, at mean springs, the great majority of the measurements used having been obtained at springs. The measurements were dense enough to permit plotting of the sea-surface for each hour referred to predicted H. W. for Le Havre, according to five principal profiles :-

The first through separate tracks in the bay of the Seine parallel to the lines of flow;

The four others perpendicular to the lines of flow approximately along the meridians of Beachy Head, Courseulles, Barfleur, Cherbourg (see Chart A). For the southern part of the meridian of Barfleur the term $\frac{V^2}{R}$ of formula (8) was taken into account, assuming that the lines of flow are centred at a point about 9 miles S. W. of Barfleur. Some fifty tidal stream stations were used; a few of them are noted on Chartlet A by means of a number from 82 in the vicinity of Fécamp to 230 near Portland, the numbers used being those of the record slips of the Tides and Geophysics Division of the " Service Hydrographique ".

The principal points, the mean springs tidal curves of which are given farther on (graphs 1-31), are marked by a number within a circle which is also the number of the corresponding graph.

The first profile (Baie de la Seine) obtained from Le Havre and referred to the tide in that port has a " closure " at Port-en-Bessin, also at Saint-Vaast.

The two east-meridian profiles are also referred to the tide at Le Havre the " closure " being in the vicinity of Beachy Head and in the vicinity of Brighton. The profiles for Barfleur and Cherbourg are referred to the tides at these harbours respectively, the " closure " being made, on the one hand, at the Isle of Wight, and on the other, at Poole Bay and Portland. For the latter part of this profile it has not been considered necessary, because of the very small reciprocal distances, to use the tidal current stations in the immediate vicinity of Portland, although complexe tidal conditions occur in that area.

(b) *Standard Tidal Curves for French Harbours.*—At the various starting-points, " standard curves " were available to the " Service Hydrographique " for mean spring tides at Le Havre (1938 records), at Port-en-Bessin (1913), Saint-Vaast (1914 and 1938), Barfleur (1920) and Cherbourg. Available data for the mean spring tide at various points along the British coast, consist of " concordances " as given by different documents and especially by the British " Tide Tables "; these records can moreover only be fragmentary owing to the very complex conditions that prevail along the British coast from Portland (double L. W.) to Portsmouth.

Without exception, times have been referred to the predicted H. W. at Le Havre, which at springs has a lag of approximately one hour on H. W. at Cherbourg. Actual H. W. at Le Havre, moreover not very well defined, follows the predicted H. W. by approximately 1.15 hour; the slack at H. W. (" tenue du plein ") is of very long duration and it is often even possible to distinguish two High Waters, particularly at equinoxial springs.

General Observations.—Tidal curves obtained by means of the computations for the above-mentioned profiles are shown on graphs 1 to 31.

Graph No. 10 relating to Port-en-Bessin shows the standard curve by means of a continuous line, and a pecked curve which has been calculated for the profile passing through point 8 (103); hourly heights have been plotted for profiles passing through points 199 and 108. Comparison permits estimation of the accuracy obtained according to various profiles orientated along the tidal lines of flow; the maximum error in range is 50 cm. for distances of about 40 miles; times very closely approximate actual times.

On graph No. 13 relating to Saint-Vaast, the standard curve is shown by a continuous line; the pecked line shows the curve as deduced from the standard curve for Port-en-Bessin ; range error is of the order of 10 centimetres ; times as computed are very close to actual times.

Finally, on graph No. 27, where a continuous line shows the standard curve for Cherbourg, the mean curve has been plotted as deduced from Le Havre by tracks 8, 14, 25, 28 totalling about 110 miles(1).

Although the range difference reaches only 75 cm., the maximum difference obtained by adjusting heights of H. W. as satisfactorily as possible reaches 1.25 metres, six hours before H. W. at Le Havre. The difference reaches 1.40 metres if the junction profile is taken through point 24, nearer Barfleur. *Therefore, it is preferable to avoid those areas where lines of flow show a marked curvature* and where complex tidal conditions prevail.

These are the only accurate checks which it was possible to make and the relative profiles are orientated principally along the tidal lines of flow in the absence of knowledge of the standard curves for the British coast (except Portsmouth).

However, partial checks are given, chiefly from the point of view of tide ranges, of times of H. W. and L. W., and the occurence of double H. W. and double L. W.

In the southern part of the two eastern profiles, range varies from 5.4 metres at point 14 (96) to 7.4 metres at point 15 (82), which means an increase of more than 2 metres ; this is largely confirmed by range at Fécamp (7.3 m.); times found for H. W. and L. W. are the same as those for Fécamp to within 10 minutes. (See Chartlet B.)

At point (18) near Beachy Head, the computed and actual range are coincident (5.9 m.); times of H. W. differ by 16 minutes only.

At point (21), near Selsea Bill, the range of 4.2 metres is intermediary between that of Selsea Bill (4.9 m.) and that of Bembridge Point (3.9 m.); times of H. W. are within 10 minutes and a gradient change appears on the curves at the beginning of the rising tide, which would occur on the actual curve for Portsmouth, forecasting the double H. W. at Southampton. The standard curve for Portsmouth has been plotted by means of a pecked line as it appears in the German tide-tables, but it should be noted that this port is about 17 miles farther N. W. than point (21) and that the change in the position of the gradient variation beween points (19) and (21) suggests that the latter must be much earlier at Portsmouth.

At point (30) near Christchurch, the range (1.8 m.), which is two-thirds that of the departure at Cherbourg (5.4 m.), is correct to within 3 decimetres. Times of double H. W. at that point and found by computation are not well defined and with actual times show differences reaching 40 minutes, although L. W. differs by more than one hour. At point (31) near Portland, the two Low Waters, showing a maximum 40-minute difference with reference to actual L. W. are again met with; the time difference between actual and calculated H. W. is half-an-hour ; range is correct to within 30 cm. (2.2 metres instead of 1.9 metre).

The average lengths of the profiles were of the order of 60 miles ; range differences ascertained were of about 30 cm. corresponding to an accuracy of the order of that obtained in the above discussion. With regard to times, which are in relatively close agreement for the two eastern profiles, the differences obtained on the western profiles may to a certain degree be explained by the large decrease in range occurring there. Maximum and minimum water-levels are as a matter of fact less well defined.

Tide in the Offing.—The above " closure " on the British coast seeming to be satisfactory enough, it appeared permissible to try to find by means of the intermediary curves, without any overall adjustment, the general characteristics of the mean spring tides at sea. Actually, a few records had been obtained in the *Baie de la Seine* with the *Favé* tide-gauge (1908-1914)—but the great majority of them during neaps, and this is known to be an area where it is not possible to deduce the characteristics of spring tides from those of neap tides, because the

(1) Calculated points are distinguishable by a cross.

amplitude does not consistently follow the tidal coefficient rule (at Brest) and the duration of the rising tide greatly varies in relation to the coefficient; in particular, mean H. W. at springs follows that of Cherbourg by about one hour (1 h. 03 m. or 1 h. 04 m.) while at neaps the lag is 1 h. 43 m.

Principal Characteristics of the Tide.—The principal characteristics of the tide for the offing are deduced on the one hand from graphs Nos. 1 to 31 (see at end) and on the other hand from the plotted co-range lines for equal times of H. W. and equal times of L. W. (See chartlet B.)

(a) *Examination of the Curves.*—Examination of the graphs reveals important tidal inequalities over the whole area, which are therefore not limited to the coastal zone, as is sometimes advanced, at least in the bay of the Seine. The phenomenon of slack of H. W. ("Tenue du plein"), noticeable in the whole eastern part of that bay, probably extends to the offing, for comparison of curves 24 and 14 suggests the presence of a zone of intermediary slack H. W. and curves 25, 26 and 30 disclose it. The axis of that area, starting from point 30 (Christchurch) would reach point 26, near 25, through the middle of 24 and 14 and point (8), then Le Havre and would continue widening from N. W. to S. E. South of the Barfleur-Fécamp line, the flat part (fr.: méplat) of the curve, sloping towards the right (after H. W.) to S. W. (curves 13, 10 and 9) corrects itself, becomes horizontal (curves 5 and 1) in the area of slack H. W., then slopes towards the left (before H. W.) on curves 3, 6, 7, 8, 14. Curve (15) which again shows a small flat part before H. W., marks the end of the large tidal anomalies. The eastern limit of the anomaly area is therefore approximately the Fécamp-Beachy Head meridian; it coincides with a rapid increase in tidal range. North of the Barfleur-Fécamp line a similar phenomenon occurs; at points 29 and 25 the flat part follows H. W. while the contrary occurs east of these points.

In this respect, then, there is great uniformity throughout the whole area.

(b) *Plotting of Equal range Curves, of Equal H. W. and L. W. times.*— The drawing of these curves for mean springs is represented on chartlet B.

The rapid decrease of the tide from Le Havre towards Poole Bay suggests the presence of the virtual amphidromic point (node) north of Portland.

Equal H. W. time curves appear in the shape of a fan centred approximately on the same point and the curve + 2 forms an arc between the Isle of Wight and Beachy Head. The chart of cotidal lines for M_2 waves drawn up by Doodson and Corkan shows a similar characteristic. The drawing was interrupted in the vicinity of the Isle of Wight because of the very long slack water.

Equal L. W. time curves have in general an aspect similar to those for Equal H. W. times except at certain points where distortion of tidal curves is very marked (near Le Havre).

III.—USE OF THE METHOD IN HYDROGRAPHIC SURVEYING.

The problem to be solved for reduction of soundings to datum consists in establishing "concordance" between the tide at different places in the offing and the coastal tide. At springs and at neaps, simultaneous observations of tides are made on the coast and of tidal streams at spots S_1, S_2, S_3, S_4 (fig. 3) in the offing. All the reduction difficulties mentioned in connection with the discussion of the bay of the Seine then disappear, and concordance at springs and at neaps is immediately obtained; which according to every probability, will give a general concordance sufficient in practice. It should be noted that, the tidal streams being more or less parallel to the coast, the profiles perpendicular to these lines should ensure maximum accuracy in the determination of the tide while at the same time corresponding to the practical needs of hydrography.

It is probable that a distance of about fifteen miles between the tidal stream stations will suffice for satisfactory determinations; besides, computations will show whether or not the gradients as found at the extremities of a same section are sufficiently close (this is very likely to be the case for such distances); if necessary a few intermediate measurements are repeated for tidal range values comparable to those encountered during the first series of measurements.

For the " closure " of the profile on shore, another line of current measurements (S_5, S_6, S_7) may be made, resecting the first line at a small angle, and a comparison of the tide obtained from this new profile S_4, S_7 B with the concordance for A and S_4 as given by the first series of measurements (fig. 3).

The following of profiles parallel to the lines of flow should be avoided, especially in the vicinity of marked indentations of the coast.

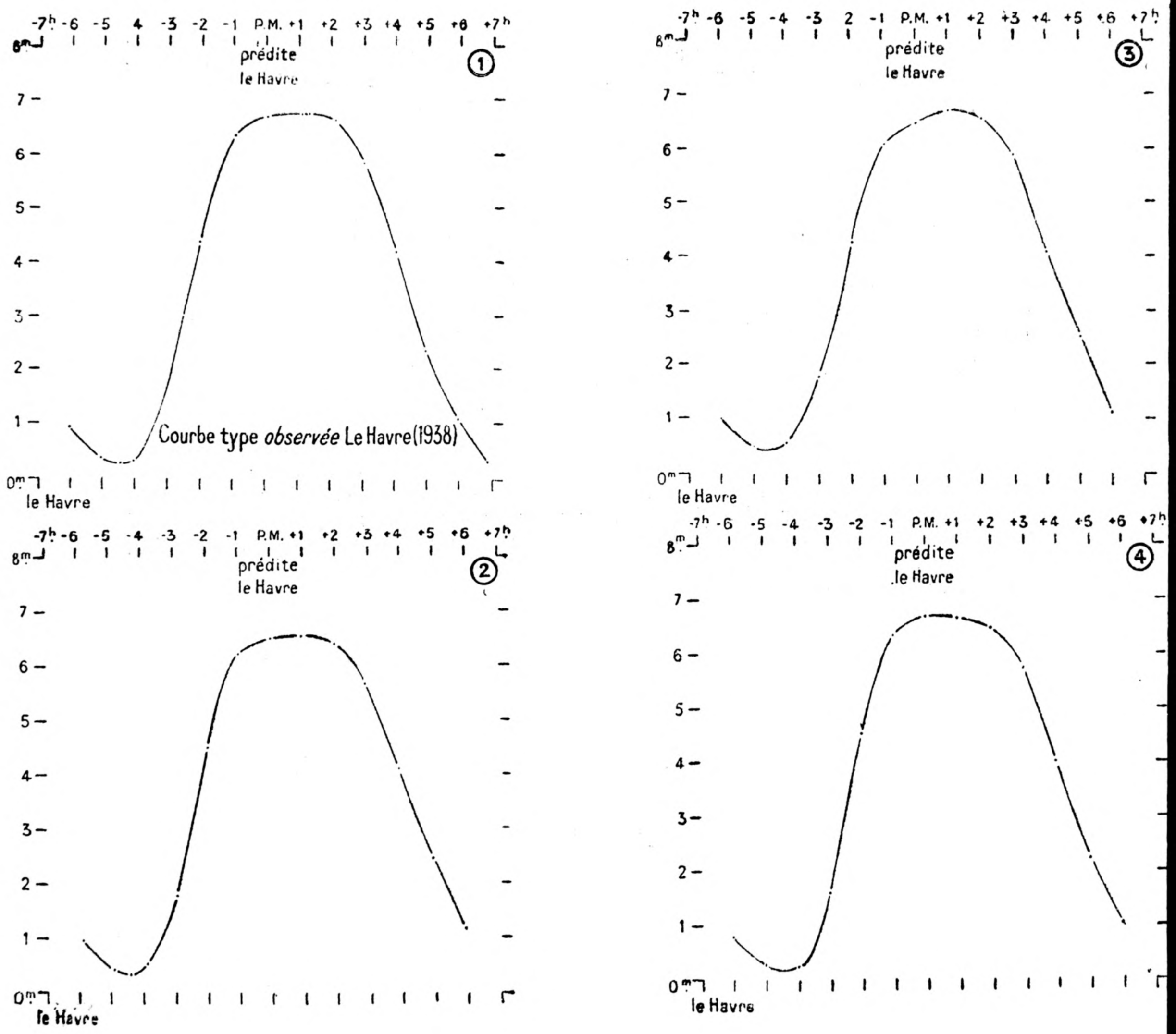
CONCLUSION.

The measurement of tidal streams in the offing during springs and neaps, in relatively shallow waters, is a current practice in surveying expeditions and is essential for ships navigating in depths greater than five to eight fathoms, when more attention is naturally paid to tidal streams than to tides.

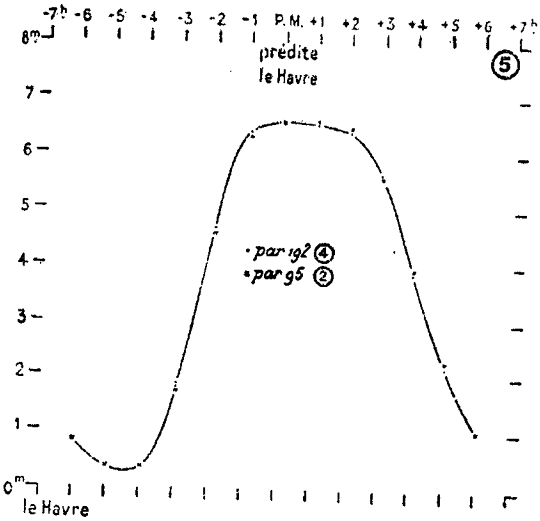
Thanks to the method developed in the preceding paragraphs, hydrographic surveying expeditions themselves may benefit from such measurements by greatly improving the accuracy of reduction of soundings to chart datum, on condition that the profile according to which the computation is made, be selected perpendicularly to the lines of flow, i.e. roughly perpendicular to the coast. It should be added that the method providing the elevation of sea level also gives the plane tangent to this surface at any instant at the tidal stream stations; whence a much more complete knowledge of the surface is obtained than through records of tides in the offing alone. Besides this practical interest which may be of value in certain sections, the introduction of the process extends our practical knowledge of the tide to the whole area over which tidal stream measurements may be made. i. e. practically up to the edge of the continental shelf.

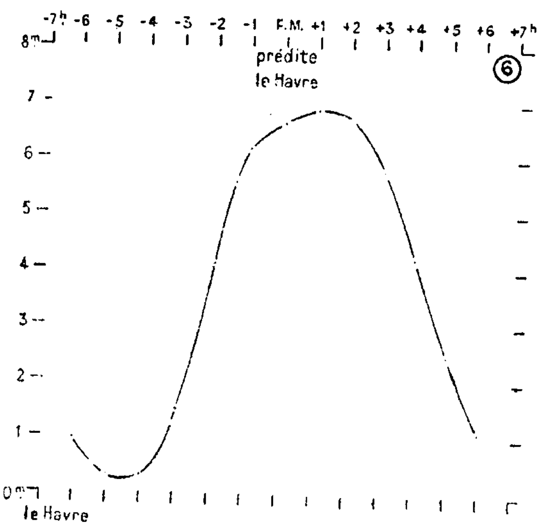
It should be mentioned that in areas where the current is slight (less than 1 knot), the relative influence on calculation of currents engendered by other causes might be of importance and confuse results. However, it is realised that the periodical character of a tidal stream permits, by means of measurements of longer duration, elimination of these foreign factors and consequently the widening of our knowledge concerning tides in all areas where sufficient current measurements may be made.

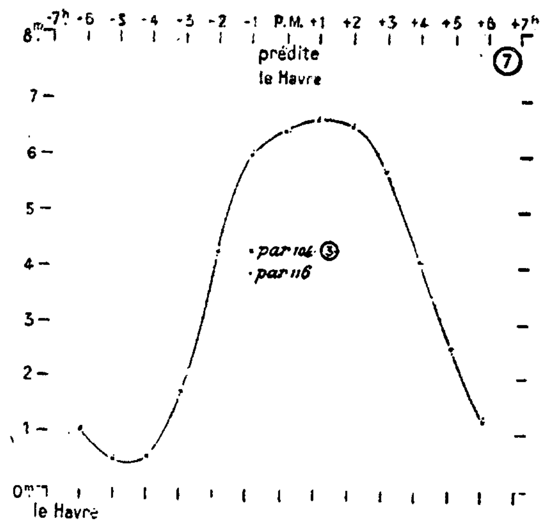
(*See Plates hereafter*)

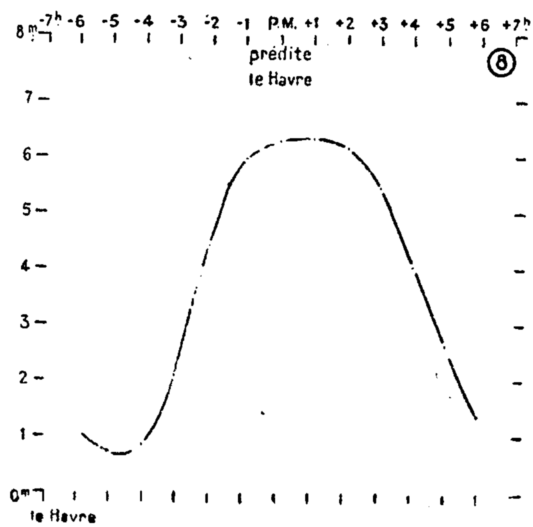


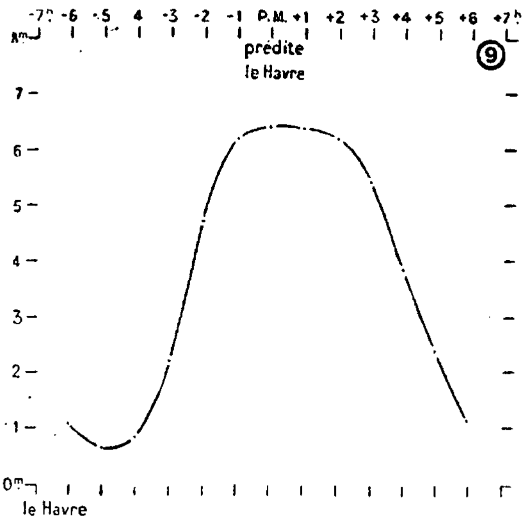
-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m 7 6 5 4 3 2 1 0m
prédite
le Havre
①
Courbe type *observée* Le Havre (1938)
le Havre
②
③
④


P.M.
prédite
le Havre
5
par 192 4
par 95 2
le Havre

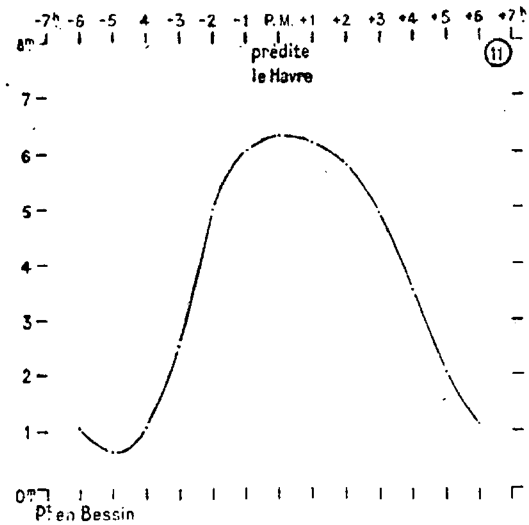

P.M.
prédite
le Havre
6
le Havre


P.M.
prédite
le Havre
7
par 116
le Havre

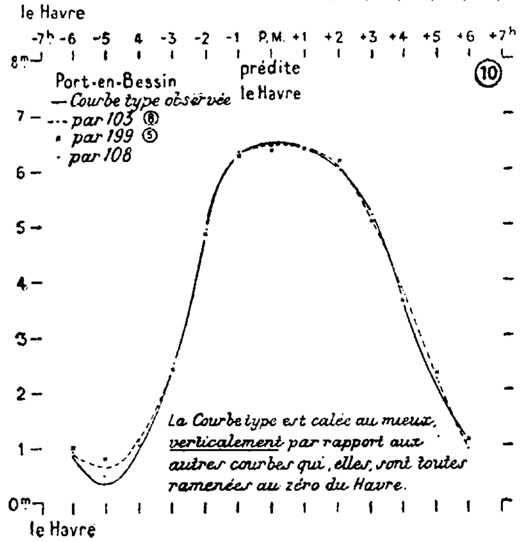

P.M.
prédite
le Havre
8
le Havre



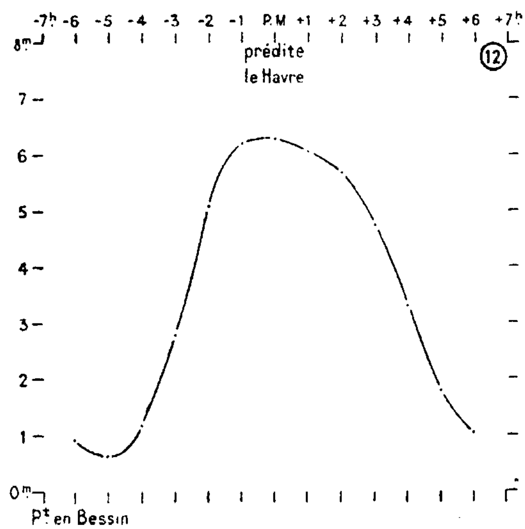
prédite
le Havre
9
le Havre



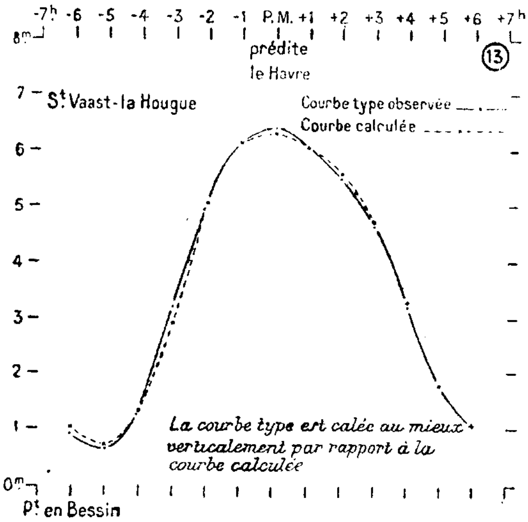
prédite
le Havre
11
Pt en Bessin

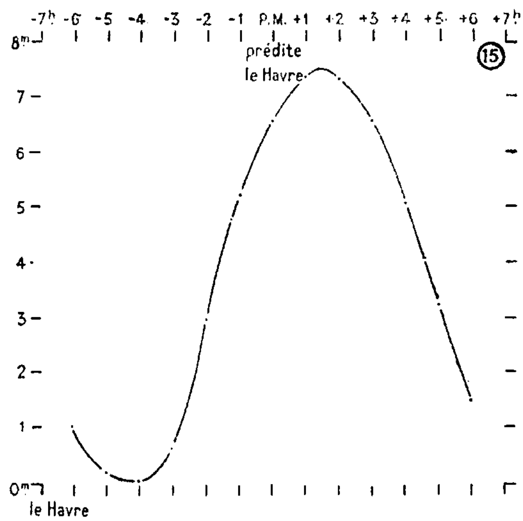


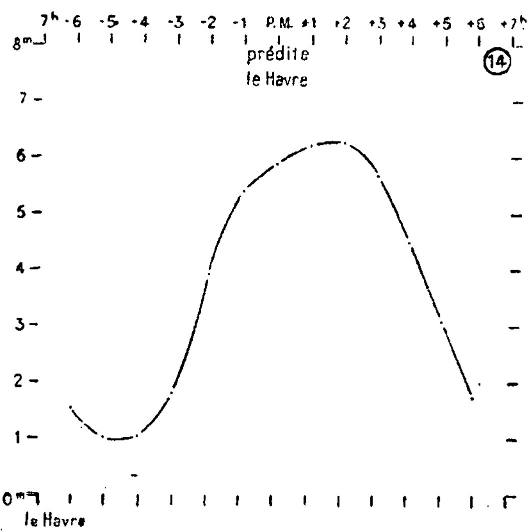
prédite
le Havre
10
Port-en-Bessin
— Courbe type observée
--- par 103 ®
• par 199 ⑤
· par 108
La Courbe type est calée au mieux, verticalement par rapport aux autres courbes qui, elles, sont toutes ramenées au zéro du Havre.
le Havre

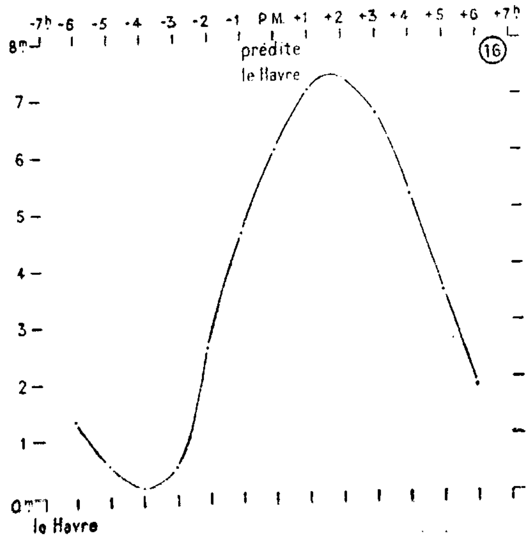


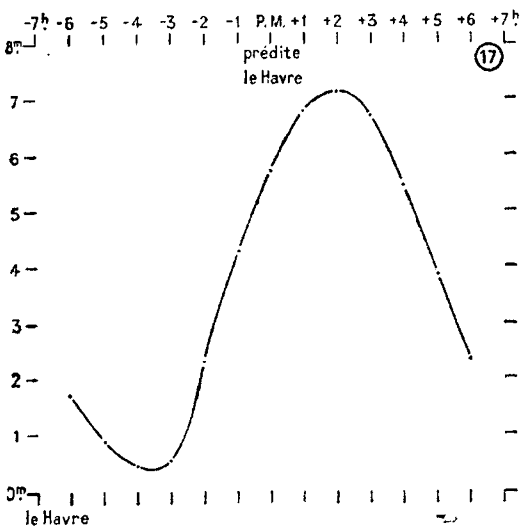
prédite
le Havre
12
Pt en Bessin

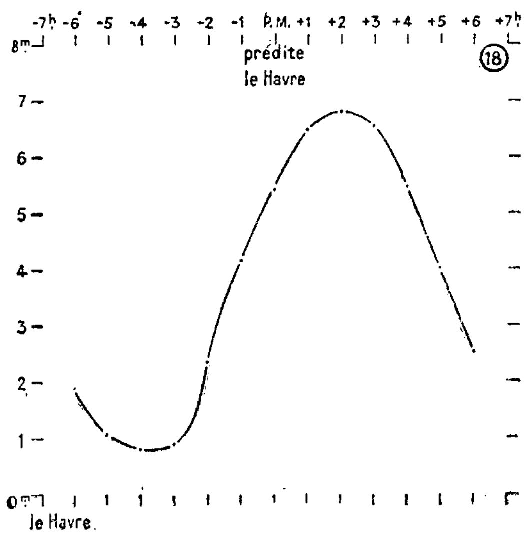

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
prédite
le Havre
13
8m
7
6
5
4
3
2
1
0m
St Vaast-la Hougue
Courbe type observée
Courbe calculée
La courbe type est calée au mieux verticalement par rapport à la courbe calculée
Pt en Bessin

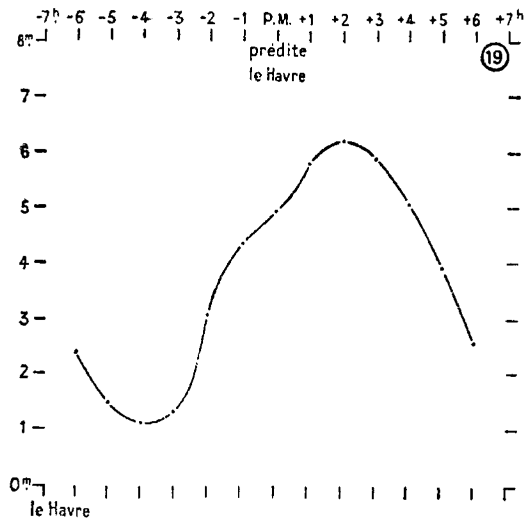

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
prédite
le Havre
15
8m
7
6
5
4
3
2
1
0m
le Havre

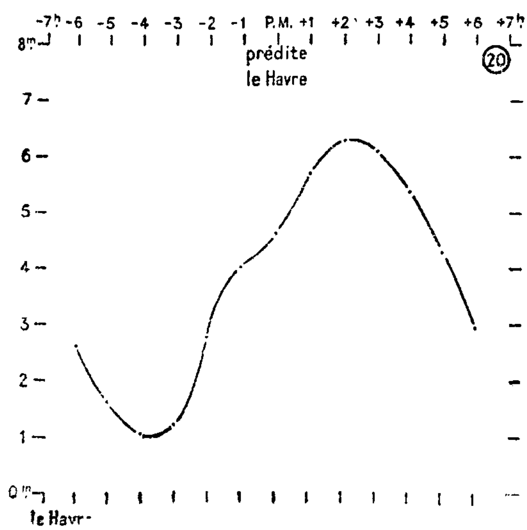

7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
prédite
le Havre
14
8m
7
6
5
4
3
2
1
0m
le Havre

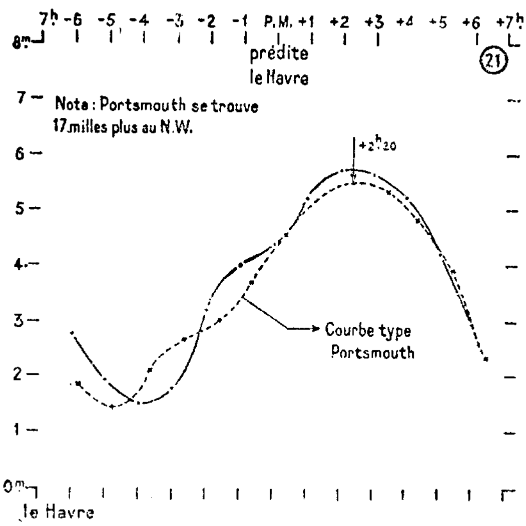

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
prédite
le Havre
16
8m
7
6
5
4
3
2
1
0m
le Havre

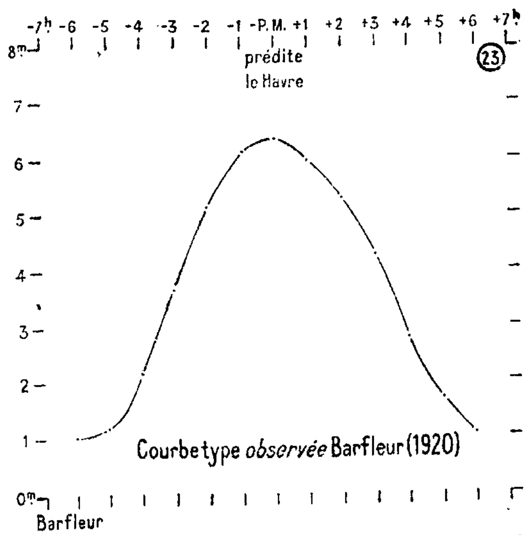

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
17
7
6
5
4
3
2
1
0m
le Havre

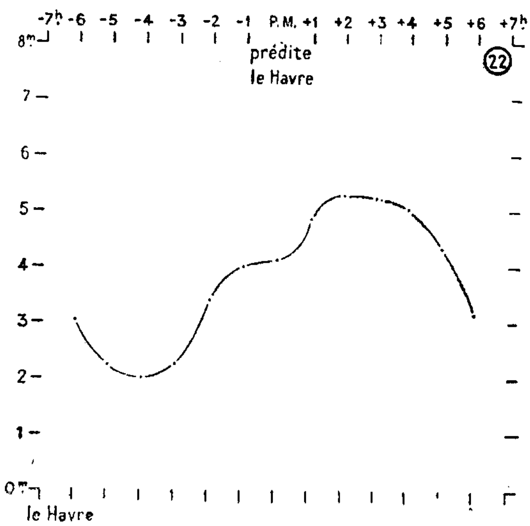

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
18
7
6
5
4
3
2
1
0m
le Havre

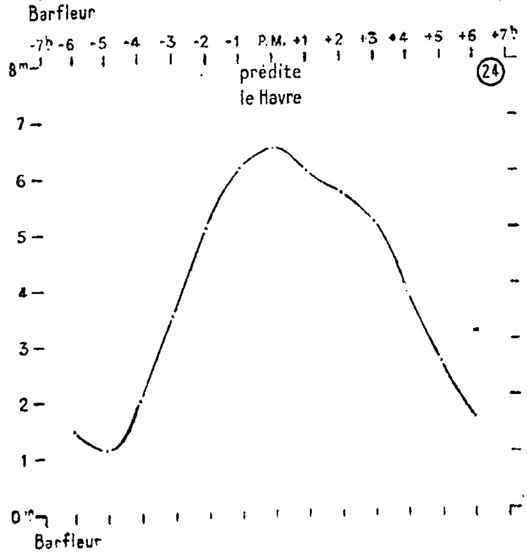

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
19
7
6
5
4
3
2
1
0m
le Havre

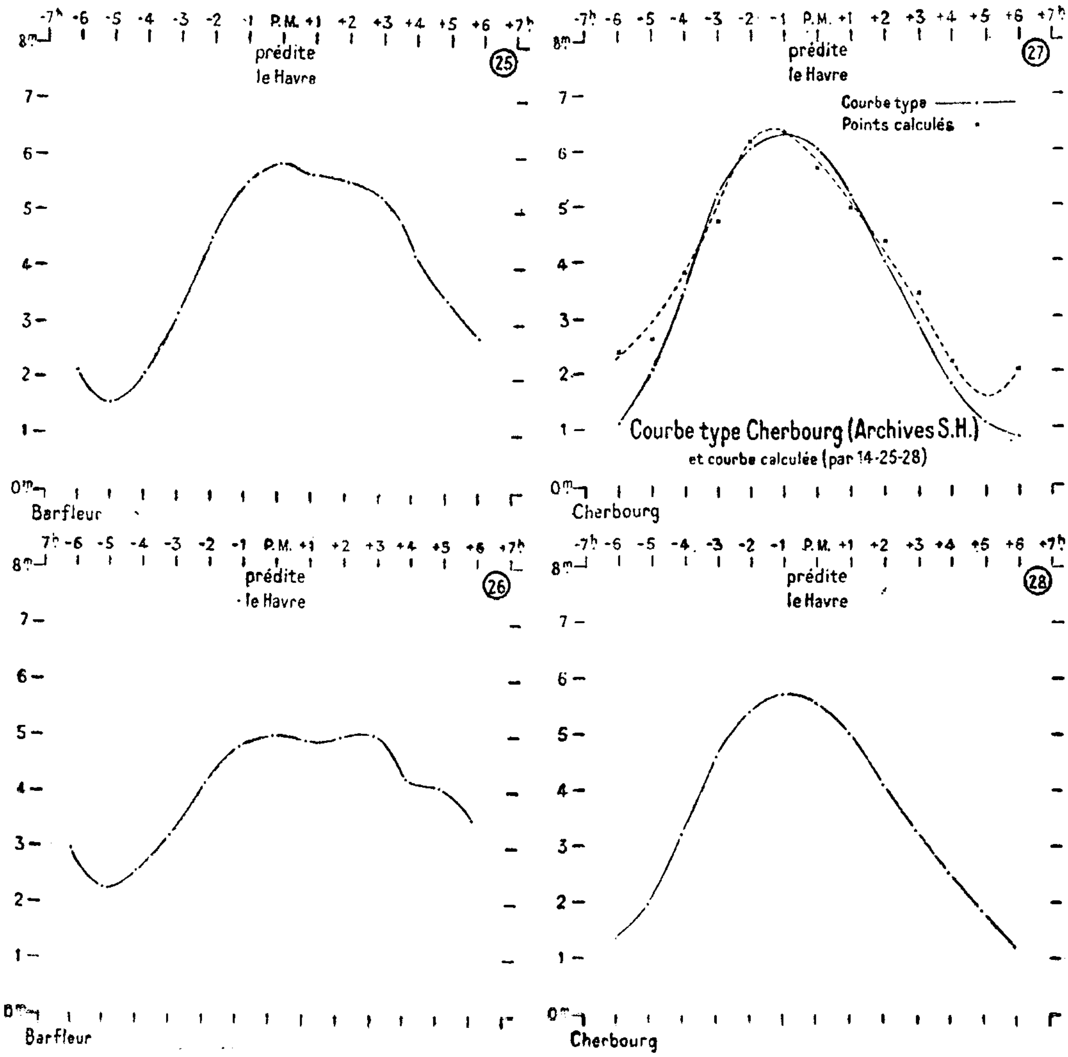

-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
20
7
6
5
4
3
2
1
0m

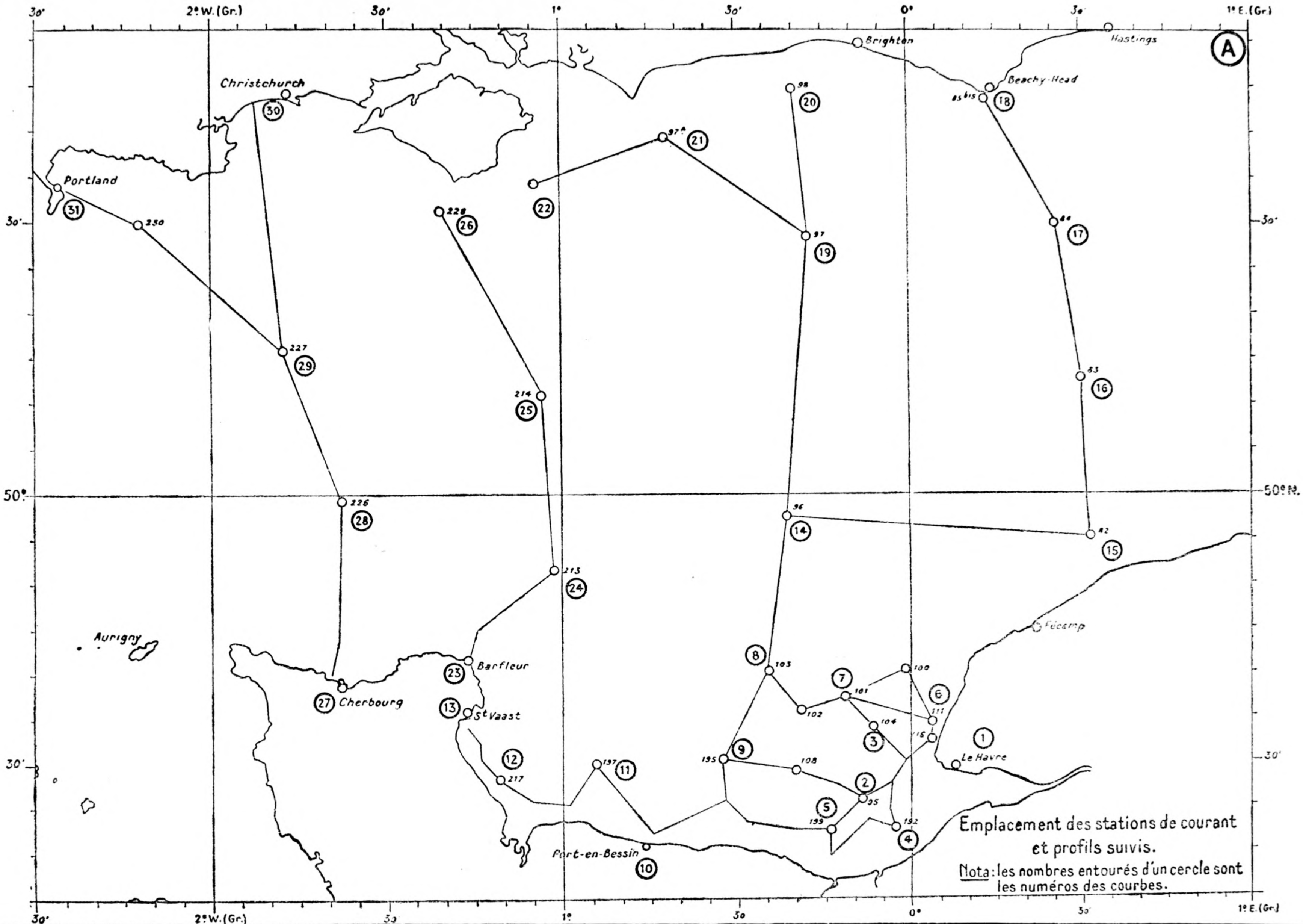

prédite
le Havre
21
Note : Portsmouth se trouve
17 milles plus au N.W.
+2h20
Courbe type
Portsmouth
le Havre


prédite
le Havre
23
Courbe type observée Barfleur (1920)
Barfleur


prédite
le Havre
22
le Havre

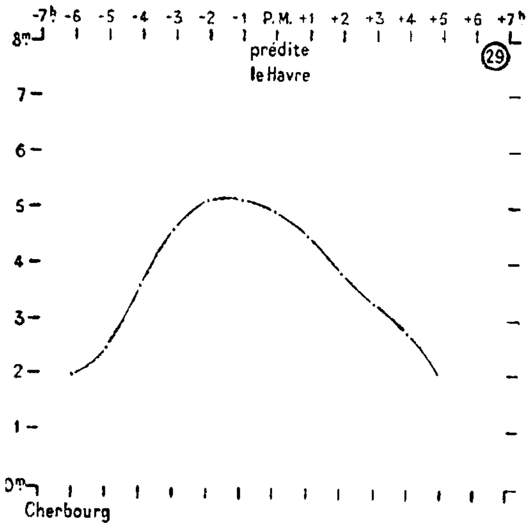

prédite
le Havre
24
Barfleur

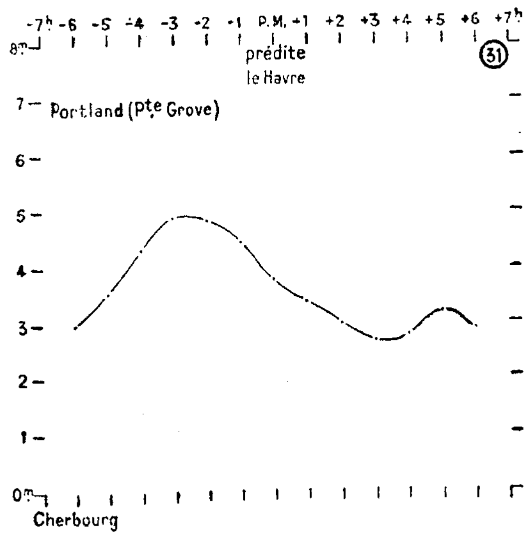

prédite le Havre
25
Barfleur
prédite le Havre
27
Courbe type
Points calculés
Courbe type Cherbourg (Archives S.H.)
et courbe calculée (par 14-25-28)
Cherbourg
prédite le Havre
26
Barfleur
prédite le Havre
28
Cherbourg

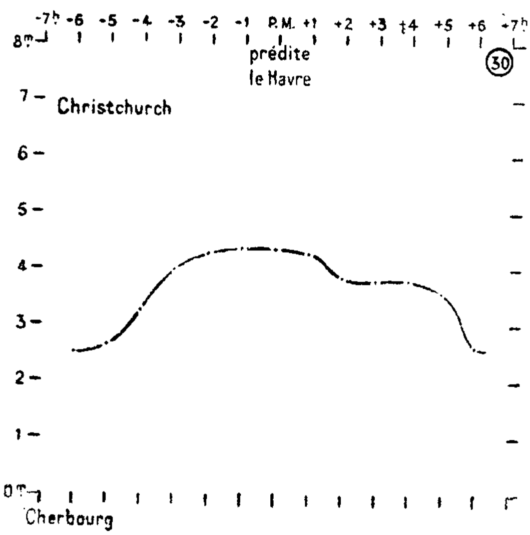


Emplacement des stations de courant et profils suivis.

Nota : les nombres entourés d'un cercle sont les numéros des courbes.


-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
29
7
6
5
4
3
2
1
0m
Cherbourg


-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
31
7
Portland (Pte Grove)
6
5
4
3
2
1
0m
Cherbourg


-7h -6 -5 -4 -3 -2 -1 P.M. +1 +2 +3 +4 +5 +6 +7h
8m
prédite
le Havre
30
7
Christchurch
6
5
4
3
2
1
0m
Cherbourg